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Could more efficient utilization of ecosystem services improve soil quality indicators to allow sustainable intensification of Amazonian family farming?

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ABSTRACT

In the Amazonian periphery, there are sources of numerous disservices, including deforestation, loss of wildlife habitat and biodiversity erosion. However, there are great opportunities to adopt appropriate agricultural management practices to take advantage of the benefits of ecosystem services for sustainable agricultural intensification. Thus, the aim of this work was to evaluate the effects of certain ecosystem services provided by combined use of legumes with residue of low- and high-quality on soil quality indicators, nitrogen use efficiency and sustainability of maize grain yield in infertile tropical soil. The overarching objective is to determine how ecosystem services can contribute to the improvement of land-use policy to ensure the sustainability of cultivated lands, in such a way that forest can be preserved by avoiding deforestation of other new areas through shifting cultivation systems. Four leguminous tree species were used, two with high-quality residues *Leucaena leucocephala* (leucaena) and *Gliricidia sepium* (gliricidia) and two with low-quality residues *Clitoria fairchildiana* (clitoria) and *Acacia mangium* (acacia). Maize grain yield was evaluated between 2011 and 2017 in these treatments. In 2018, to assess how ecosystem services affect crop performance, the treatments were divided into ten treatments with and without urea. We conclude that increased uptake of inorganic and organic N by maize resulting from improvement of the soil quality indicators may allow agricultural intensification. This improvement can help meet the challenges of sustainability and feasibility of agroecosystems of the Amazonian periphery by making the agroecosystem more productive year by year. Therefore, our results confirm that the utilization of an ecosystem services style approach can help meet the challenges of sustainability and feasibility in agrosystems of the Amazonian periphery. In addition, these results can contribute to the development of land-use policy in the Amazonian periphery, aiming for the intensification of agriculture in cropped areas to avoid deforestation of new areas from shifting cultivation systems.

1. Introduction

Agriculture in the Amazonian periphery can cause numerous disservices, including deforestation and loss of wildlife habitat, soil nutrient depletion, greenhouse gas emissions, and loss of biodiversity (Power, 2010). In contrast, there are excellent opportunities to adopt appropriate agricultural management practices to realize the benefits that ecosystem services can provide to improve soil quality indicators such as carbon sequestration, maintenance of soil organic matter, nutrient cycling and increased soil fertility (Prado et al., 2016; Aguiar et al., 2013). Drawing largely on Fisher et al. (2009) ecosystem services is considered here as ecological process of ecosystems utilized to produce human well-being. Specific opportunities relate to use of high biodiversity, combining long growing seasons with adequate soil moisture and consistent year-round warm weather. These conditions allow farmers to take advantage of fast tree growth, nitrogen-fixing legumes and high biomass production, which may be converted into soil organic matter and recycled nutrients (Berenguer et al., 2018). Although land

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use change for food production has, in some cases, led to improved livelihood and poverty alleviation, the extensive change in forest cover in the Brazilian Amazon has not had such an effect (Pinho et al., 2014). In contrast, inappropriate use of natural resources has often led to a vicious cycle in which poverty increases pressure on natural resources, and, in turn, the degradation of natural resources increases poverty (Moura et al., 2013). Therefore, agriculture in this region faces huge challenges to reverse this process regarding environmental sustainability and social-economic feasibility, which may be aggravated by global warming (FAO et al., 2018).

Fortunately, a wide range of statistical analyses have shown that agricultural research on increased food production may be beneficial for impoverished areas such as the Amazonian periphery, where 75% of poor people work and live in rural environments

(Mendola, 2007; Anríquez and Stamoulis, 2007). In this region, as in many parts of the world, while the growth of agricultural production will depend more and more on yield-increasing technological changes, the poor are often highly dependent on the available ecosystems for their livelihood (Huq et al., 2020). Compared to other approaches for addressing compatibility between environmental policy and agricultural development, ecosystem services approaching have the advantage of facilitating interaction among sectors of society involved in the management of ecosystems and can influence public and private decisions, reconciling conservation and development goals (Weyland et al., 2019).

Challenges for agricultural sustainability in the Amazonian region are mainly associated with depletion of soil chemical fertility and worsening of soil physical properties. Decline in chemical fertility results from reduced nutrient availability in soils dominated by low activity clays, which has low capacity to retain nutrients under high rainfall intensity, leading to a high rate of nutrient loss from leaching (Glaser et al., 2002). Worsening of physical properties is due to hardening, which occurs during drying cycles because of reduced soil organic matter, when continuous use is made to soil with low iron content (Daniells, 2012). Both increased nutrient loss and hardening are closely related to nutrient use efficiency and can be addressed by organic carbon sequestration and nutrient cycling provided by ecosystem services (Prado et al., 2016).

Fortunately, there are certain advantages which researchers and farmers can use to meet the challenge of achieving a desirable scenario for tropical agriculture. First, fast tree growth and high biomass production, which may be converted into soil organic matter, increase availability of recycled base cations for crops, improving the environment of the root zone (Malhi, 2012; Berenguer et al., 2018). Second, biomass applied to the soil surface can delay soil drying, increasing water availability (Muller et al., 2017). Together, remaining water and soil organic matter may enhance soil rootability and water-and nutrient-use efficiency (Moura et al., 2018). Last but not least, tropical leguminous trees, when associated with high tropical biodiversity of bacteria with high nitrogen-fixing efficiency, can produce biomass with high nitrogen content, increasing soil nitrogen availability (Coelho et al., 2018).

Therefore, to ensure the economic feasibility of tropical agroecosystems, provision of ecosystem services must be mainly directed towards improvement of the environment of the root zone for root growth and increasing nutrient availability and plant uptake. Mulching with surface residues has been recommended, as it provides soil cover and decreases the water evaporation rate, delays soil moisture loss, increases soil organic matter, improves soil rootability, and releases nutrients after decomposition (Jun et al., 2014). However, the effect of mulching is closely related to the quality of residues used as soil cover (Finney et al., 2016). According to Tian et al. (1995) high-quality plant residues (low C/N ratio, low lignin and polyphenol contents), which decompose fast, can have a direct nutritional effect as green manure. Low-quality (high C/N ratio, high lignin and polyphenol contents) plant residues, which decompose slowly, may have greater effects on soil water evaporation, increased soil organic matter and, consequently, soil rootability (Mulumba and Lal, 2008). Thus, a strategy for efficient harnessing of ecosystem services, to ensure sustainability and feasibility of Amazonian agroecosystems, must include the use of both residues of high and low quality.

In this work, we hypothesize that, if strategically used, the environmental advantages of the humid tropics may provide ecosystems services capable of overcoming the challenge of developing sustainable and feasible agricultural systems in the Amazonian periphery. Thus, the aim of this work is to evaluate the effects of low- and high-quality leguminous residues on base cations and soil organic matter of the soil root zone, nitrogen uptake, nitrogen use efficiency and sustainability of maize grain yield in infertile tropical soil. The overarching objective is to determine how improvement in soil quality indicators provide by ecosystem services approaching can contribute to the improvement of land-use policy to ensure the sustainability of cultivated lands, in such a way that forest can be preserved by avoiding deforestation of other new areas through shifting cultivation systems.

2. Materials and methods

2.1. Experiment site

This study was conducted between 2009 and 2018 at Maranhao Federal University in Chapadinha, Maranhao, Brazil (3°44′30″S and 43°21′37″W). The region has a semi-humid equatorial climate, with average temperature of 29 °C and maximum of 37 °C at 110 m above sea level. The rainy season occurs between December and May. The soil in the experimental area is an Arenic Hapludult, with chemical and textural characteristics described in Table 1.

2.2. History of the experimental area

The area was fallow for five years after cultivation in a slash-and-burn system. To increase the percentage base saturation to 60%, the area was limed in January of 2009 using a surface application of 2 Mg ha^{-1} limestone. In 2014, 6 Mg ha^{-1} of agricultural gypsum was applied in the experimental area to increase the calcium content in the root zone. The experiment was established with four leguminous tree species, two with high-quality residues *Leucaena leucocephala* (leucaena) and *Gliricidia sepium* (gliricidia) and two with low-quality residues *Clitoria fairchildiana* (clitoria) and *Acacia mangium* (acacia). The legume residue quality was determined based on C/N ratios, as described by Tian et al. (1995) and Aguiar et al., (2010). Analyses of these leguminous residues are presented in Table 2.

The legumes were planted in January of 2009 with a spacing of 0.05 m in 10 × 4 m plots and in mixed rows so that each parcel received the two quality residues (Fig. 1), totalling four combinations as follows: CG = Clitoria + Gliricidia; AG = Acacia + Gliricidia; CL = Clitoria + Leucaena; AL = Acacia + Leucaena.

The area remained fallow in 2010, and pruning of legume branches first occurred in January 2011, with annual cuttings in January of each year until 2018 at a height of approximately 50 cm. Quantities of biomass applied from 2010 to 2018 are shown in Table 3.

From 2011 − 2017, maize was grown under a no-tillage system between the rows of the leguminous plants. The soil was fertilized in each of these years with 80 kg ha^{-1} P_2O_5, 60 kg ha^{-1} K_2O and 5 kg ha^{-1} Zn. In addition, 100 kg ha^{-1} of nitrogen was applied, divided into two applications. At physiological maturity the maize gain yield was determined in a 12 m^2 area, and all values were adjusted according to a moisture level of 145 g kg^{-1}.

2.3. Description of the nitrogen and maize experiment in 2018

In order to establish and assess the link between ecosystem services provide by leguminous trees and social-economic benefits, in January 2018 an experiment was initiated in the same area to evaluate the effects

Table 1

Characteristics of soil of the experimental area before the beginning the experiment. Soil organic matter (SOM), sum of base (SB), percentage base saturation (PBS).

Layer	SOM	pH	P	K	Ca	Mg	SB	PBS	Clay	Silt	Sand
cm	g dm^{-3}	CaCl$_2$	mg dm^{-3}	mmol$_c$ dm^{-3}				%	g kg^{-1}		
0–5	34	5	9	1	25	5	33	40	25	5	70
5–10	32	5	11	1	19	4	25	28	27	5	68
10–15	30	4	6	0.3	11	2	14	14	29	7	65
15–20	26	4	4	0.2	6	2	8	9	32	5	63
20–40	21	4	4	0.2	4	1	5	6	31	8	61

Table 2

Chemical analyzes of leguminous residues.

Legumes	C/N	N	P	K	Ca	Mg
		g kg^{1}				
Leucaena	11.48	43.53	2.71	6.72	3.8	3.69
Gliricidia	13.51	37.01	1.48	4.62	3.26	2.33
Clitoria	18.38	27.21	3.15	5.89	3.75	2.39
Acacia	23.45	21.32	2.57	4.22	2.99	2.09

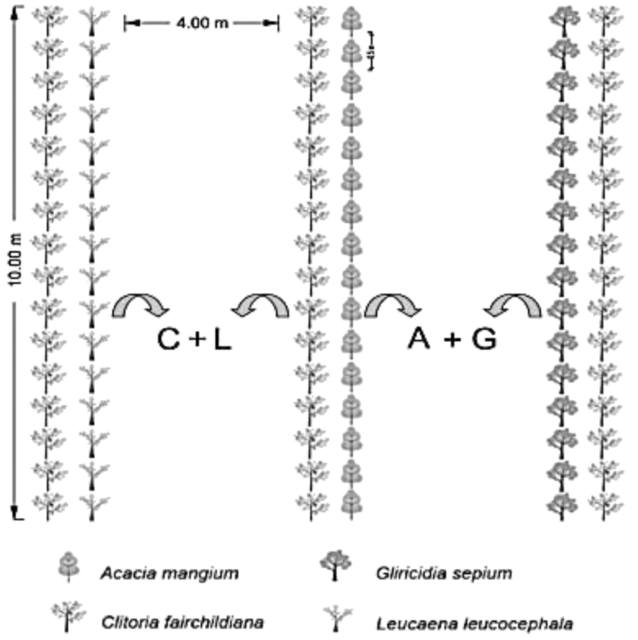

Fig. 1. Diagram of an experimental plo, C + L = Clitoria + lLeucaena; A + G = Acacia + Gliricidia.

Table 3

Dry biomass of the tree legume combinations applied to the soil from 2010 to 2018.

	2011	2012	2013	2014	2015	2016	2017	2018
	Mg ha^{-1}							
CL	5.90	6.30	8.20	7.88	8.50	9.50	12.00	4.4
AL	6.30	3.20	8.50	7.10	7.80	8.00	11.00	4.7
CG	13.10	6.70	16.00	10.40	13.20	12.51	16.00	4.4
AG	17.60	5.20	12.90	9.57	11.50	13.20	15.00	4.7

CL = clitoria + leucaena; AL = acacia + leucaena; CG = clitoria + gliricídia and AG = acacia + gliricidia.

of leguminous biomass on nitrogen harnessing and maize yield. The leguminous trees were pruned, and the combinations of biomass were adjusted according to the N content to provide 150 kg N ha^{-1} of organic N via vegetable residues. Just after the cutting and application of the biomass to soil, the maize (cultivar 30f35 Pioneer) was sown in a spacing of 0.90 m × 0.20 m. The treatments consisted of the combinations of legumes without and with urea, totalling ten treatments: clitoria + leucaena with urea (CLU), clitoria + leucaena (CL), acacia + leucaena with urea (ALU), acacia + leucaena (AL), clitoria + gliricidia with urea (CGU), clitoria + gliricidia (CG), acacia + gliricidia with urea (AGU), acacia + gliricidia (AG), bare soil with urea (BSU) and bare soil (BS). Fertilization consisted of application of 100 kg ha^{-1} of P_2O_5 and 60 kg ha^{-1} of K_2O, using triple superphosphate and potassium chloride sources. At planting, only selected plots received 60 kg ha^{-1} of N via urea. In both the four- and eight-leaf stages, fully developed, two nitrogen fertilizer applications were made as side-dressing, employing a total of 70 kg ha^{-1} N via urea, only in plots that received N at planting.

2.4. Samplings and soil analysis

To undertake the analyses of soil chemistry and physical fractionation of soil organic matter, in May 2018 soil samples were collected with a probe-type auger. A total of 9 simple samples per plot were collected to obtain a composite sample at depths of 10–30 cm. Samples from each plot were air-dried and passed through a 2 mm sieve before analysis.

The soil organic matter was physically fractionated, according to the methods of Cambardella and Elliott (1992). Air-dried soil samples of 20 g were sieved through 2 mm mesh and weighed in 250 ml polyethylene cups, to which 80 ml of 5 g L^{-1} sodium hexametaphosphate was added. Each mixture was shaken for 15 h in a horizontal shaker, with 130 oscillations min^{-1}. After this process, the entire contents of each vial were placed into a 0.053 mm mesh sieve and washed with a weak jet of distilled water until the clay was completely removed. The material retained on the sieve was defined as total particulate organic matter (>53 μm) and was dried at 50 °C. After drying, each sample was ground in a porcelain mortar, after which an aliquot was collected, weighed and analysed for its C content, representing the soil particulate organic carbon (POC) in particulate organic matter, according to the Walkley-Black method. An aliquot of the 2-mm sieved subsample was ground in a porcelain mortar and weighed and analysed for the analysis of soil total organic carbon (TOC). Soil mineral-associated organic carbon (MOC) was calculated as the difference between TOC and POC. The total organic carbon stock (TOCS) of each of the 0 – 30 cm layers was calculated by the following expression (Veldkamp, 1994): TOCS = (TOC × ρs × E)/10, where TOCS = organic C stock at a given depth (Mg ha^{-1}), TOC = organic C content at the sampled depth (g kg^{-1}), ρs = soil bulk density (kg dm^{-3}), and E = thickness of the layer (30 cm). Soil organic matter (SOM) was calculated by multiplying TOC by 1.74, and accumulated soil organic matter (ASOM) was calculated as the difference between ASOM of the treatment and ASOM of the control (BS).

Soil samples were analyse for exchangeable K, Ca, and Mg using an exchangeable ion resin (Van Raij et al., 1986). Ca, Mg, and K measurements were obtained using a Varian 720-ES ICP Optical Emission Matter Analysis Spectrometer. The sum of bases cations (SBC) was calculated as: K + Ca + Mg. Accumulated sum of base (ASB) of Ca, Mg and K, in kg ha^{-1}, in the 0–30 cm layer of the soil profile, were calculated according to the equation of Ellert and Bettany (1995): ASB = SBC × ρs × 30, where SBC = sum of base cations (mg kg^{-1}), ρs = soil bulk density (Mg m^{-3}). The accumulated sum of bases (ASB, in kg ha^{-1}) was calculated as the difference in means between ASB of treatments – ASB in the Bare Soil (BS).

2.5. *Plant analysis, efficiency indices and yield components*

Dry matter and N content were measured at tasselling and at physiological maturity. At each sampling time, five maize plants from each plot were randomly selected and all of the plant materials were dried at 60 °C for 3–4 days to obtain a constant weight when the stover yield was measured. Sub-samples were ground to pass through a 1-mm screen. The N concentration was determined following the H_2SO_4 –H_2O_2 digestion method, according to Temminghoff and Houba (2004). Total plant N accumulation was determined by adding the grain and whole plant N accumulation values, which were calculated by multiplying the maize dry biomass by the respective maize tissue N concentrations. Based on dry matter (DM) and N absorbed, these parameters were calculated:

- Total N (TN) = *nitrogen accumulation in the plant + nitrogen accumulation in the grains*;
- Biological nitrogen use efficiency (BNUE) = *((N accumulation in the plot with vegetable residue - accumulation of N in the control) × 100)/ N applied via vegetable residue)*;
- Inorganic nitrogen use efficiency (INUE) = *((N accumulation in plot with urea - N accumulation in plot without urea) × 100)/ N applied via urea)*;
- Nitrogen agronomic efficiency (NAE) = *(grain production in the plot with urea) / N applied via urea.*

Again, in 2018 the maize grain yield was determined at the final harvest or at physiological maturity, which was assessed in a 12 m^2 area, and all the values were adjusted according to a moisture level of 145 g kg^{-1}. The data obtained through these evaluations were submitted to analysis of variance (ANOVA), with their means compared by the Duncan's post-hoc test at a $P = 0.05$ significance level. Statistical analyses were carried out using InfoStat software (InfoStat Group, College of Agrarian Sciences, National University of Córdoba, Córdoba, Argentina).

3. Results

3.1. *Impact of ecosystem services on environment of the soil root zone*

From the fifth year combined biomass application was capable of maintaining a higher sum of base cations (SBC) at the 30-cm layer such that, after eight years, SBC was more than 50% greater in all treatments with biomass compared to bare soil (BS), especially in the CG treatment, where it was 60% greater (Table 4). However, the accumulated sum of base (ASB) more clearly highlights the benefit provided by combination of leguminous biomass. More than 1.6 tons per hectare of ASB were recycled or maintained in the root zone by application of leguminous tree biomass, reaching up to 2.1 tons in the CG treatment.

Biomass application also increased total organic carbon (TOC) in all treatments ($P < 0.05$); however, the increase was due to differences in particulate organic carbon (POC), which was 60% greater in CL than in the treatments with bare soil (Table 5). There was no difference among treatments in leaked-mineral organic carbon fraction (MOC), where all means are represented by letter "a". Differences in TOC content between treatments with and without biomass were approximately 20%. There were also increases in total organic carbon stock (TOCS) and soil organic matter (SOM) in the soil root zone due to biomass application. Although accumulation was greater in the treatments with biomass, even in control conditions SOM did not decrease compared to the beginning of the experiment. However, accumulated soil organic matter due to biomass application was higher than 0.58% in all treatments, reaching up to 0.85% in the CG treatment.

3.2. *Effects of ecosystems services on maize grain yield, in the seven years of the experiment*

Ecosystem services provided by legumes were capable of sustaining maize grain yield growth during the seven years of the experiment (2011 to 2017), in such a way that grain yield increased and was higher in treatments with legumes ($P < 0.05$) from 2013 up to 2017 (Fig. 2). Thus, in the third year (2013), with lower rainfall index, maize grain yield was six times greater in the clitoria with leucaena (CL) treatment than in bare soil (BS). Treatment CL was superior to other treatments with biomass in 2016. In 2015 and 2017 maize grain yield was higher in CL than in CG and AL.

3.3. *Ecosystem services effect on nitrogen uptake, dry matter, grain yield and nitrogen use efficiency of maize in 2018*

Total N accumulated by maize was increased by leguminous biomass application, in such a way that in the treatment with urea alone (BSU) it was more than 66% lower than in the other treatments with urea and biomass (AGU, CLU, CGU and ALU) (Fig. 3A). On the other hand, leguminous biomass alone increased N uptake more than 2.5 times compared with the BS treatment. However, when without urea, only in the treatments with gliricidia (AG and CG) was total N content not lower than in the treatment with urea alone ($P < 0.05$). The inorganic nitrogen use efficiency (INUE) was elevated by leguminous biomass, except in the CGU treatment where it was not different from BSU (Fig. 3B). In contrast, the combinations CL and AG increased INUE more than 37%.

Maize dry matter production also increased in response to biomass with and without urea, but the differences were larger when urea was not used ($P < 0.05$). Biomass also increased maize grain yield in 2018 (Fig. 4). Increase in grain yield due to biomass was 52% when CLU and BSU are compared and 170% when CL and BS are compared, indicating the impact of ecosystem services provided by legumes on maize productivity.

Inorganic nitrogen increased biological nitrogen use efficiency (BNUE) in the combinations with leucaena (CL) and (AL), in such way that in CLU it was 66% higher than in CL (Fig. 5A). Furthermore, in CL and AL BNUE was also lower than in CGU and AGU ($P < 0.05$). Nitrogen agronomic efficiency (NAE) was positively affected by biomass except in

Table 4
Sum of base cations (SBC) and accumulated sum of base (ASB) at 0–30 cm layer, from 2010 to 2018.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	ASB kg ha^{-1}
	SBC $mmol_c$ dm^{-3}									
CL	20.2 a	42.34 a	41.32 a	40.56 a	64.85 a	62.98 a	63.66 a	63.20 a	63.48 a	1.669 c
AL	19.5 a	42.30 a	40.83 a	39.43 a	65.58 a	64.67 a	64.53 a	63.56 a	65.44 a	1.829 b
CG	21.4 a	43.10 a	41.56 a	40.23 a	67.61 a	68.75 a	69.93 a	70.20 a	69.11 a	2.130 a
AG	21.0 a	42.60 a	41.78 a	39.58 a	65.18 a	64.65 a	65.7 2 a	66.48 a	66.94 a	1.951 b
BS	20.5 a	40.53 a	38.43 a	36.34 a	46.90 b	45.87 b	47.12 b	44.62 b	43.08 b	–

CL = clitoria + leucaena; AL = acacia + leucaena; CG = clitoria + gliricídia, AG = acacia + gliricidia; BS = Bare Soil.
Different letters in the same column indicate differences at the 5% level by Duncan's test.

Table 5

Particulate organic carbon (POC), mineral associated organic carbon (MOC) and total organic carbon (TOC) separated by physical fractionation, total organic carbon stock (TOCS), soil organic matter (SOM) and accumulated soil organic matter (ASOM) in the 0–30 cm depth.

	CLU	AGU	CGU	ALU	CL	AG	CG	AL	BSU	BS
POC (g kg^{-1})	13.14 ab	12.74 ab	13.66 ab	14.27 ab	16.01 a	10.70 ab	12.32 ab	12.92 ab	9.91 b	9.91 b
MOC (g kg^{-1})	10.79 a	11.49 a	10.88 a	9.21 a	7.70 a	13.98 a	12.69 a	11.99 a	11.66 a	10.14 a
TOC (g kg^{-1})	23.93 a	24.24 a	24.54 a	23.48 a	23.71a	24.68 a	25.01 a	24.90 a	20.47 b	20.05 b
TOCS (Mg ha^{-1})	70.34 a	71.26 a	72.14 a	69.02 a	69.07 a	72.54 a	73.52 a	73.20 a	60.18 b	58.94 b
SOM (g kg^{-1})	41.15 a	41.71 a	42.20 a	40.38 a	40.78 a	42.44 a	43.01 a	42.82 a	35.20 b	34.48 b
ASOM (g kg^{-1})	6.67	7.23	7.72	5.90	6.30	7.96	8.53	8.34		

CLU = clitoria + leucaena with urea. AGU = acacia + gliricidia with urea. CGU = clitoria + gliricidia with urea. ALU = acacia + leucaena with urea. CL = clitoria + leucaena. AG = acacia + gliricidia. CG = clitoria + gliricidia. AL = acacia + leucaena. BSU = bare soil with urea. BS = bare soil.
Different letters in the same row indicate differences at the 5% level by Duncan's test.

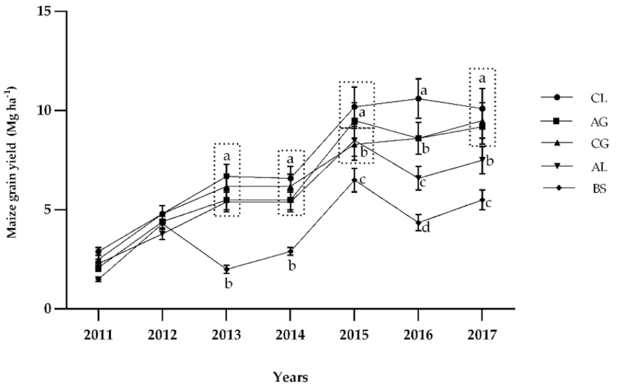

Fig. 2. Maize grain yield in Mg ha^{-1} from 2011 to 2017. Different letters indicate differences at the 5% level by Duncan's test.

the ALU treatment. Meanwhile, NAE was 52% greater in the CLU treatment than in the BSU treatment (Fig. 5B).

4. Discussion

4.1. Biomass and SBC interactions

To discuss the elevated SBC and SOM promoted by biomass in this experiment, it is necessary to consider interactions between base cations and soil organic matter fractions as described by Ellerbrock and Gerke (2018). Thus, the positive effect of the leguminous biomass on SBC content can be explained not only by the quantity of nutrients recycled by legumes but also by the increased capacity of soil to retain base cations, caused by compounds derived from biomass decomposition (Lützow et al., 2006). Furthermore, these polyvalent cations interact with functional groups of SOM by forming cation bridges, leading to the relative stabilization of SOM (Moore and Turunen, 2004). The bonds between polyvalent cations and negatively charged organic matter functional groups are not easily reversible, and surfaces of organic materials will be least accessible for microbial activity (Whittinghill and Hobbie, 2012). In fact, even though rapid biomass decomposition (Hijbeek et al., 2018) and high rates of base leaching (Glaser et al., 2002) occur in the humid tropics, these results suggest the possibility of making use of alternative ecosystem services to avoid land degradation, combining the maintenance of adequate levels of SOM and SBC.

In addition, another important insight from this experiment is that calcium as an amendment may strengthened the effects of ecosystem services by increasing maize grain yield. Indeed, improved land quality as shown by Tables 4 and 5 was followed by increased maize grain yield, which was sustained by six years of continuous cropping, especially after gypsum application in 2014 when maize grain yield reached a higher level. It is worth highlighting the greater effect on maize grain yield after increasing time following biomass application indicated by the maize grain yield lines (Fig. 2). Larger differences between control and CL treatments in 2013 suggest greater effects of this biomass combination

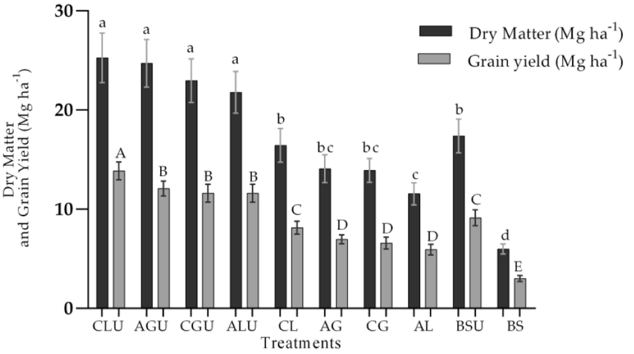

Fig. 4. Dry matter and maize grain yield. Different letters indicate differences at the 5% level by Duncan's test.

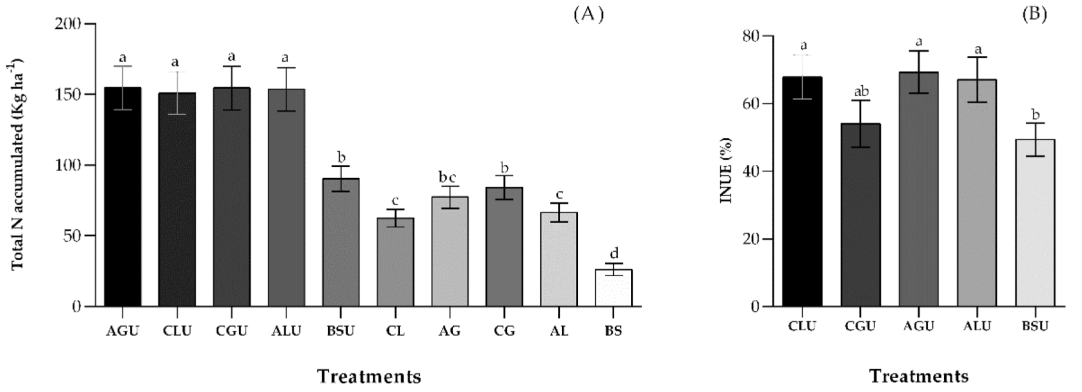

Fig. 3. Total nitrogen accumulated (A); Inorganic nitrogen use efficiency (INUE) (B). Different letters indicate differences at the 5% level by Duncan's test.

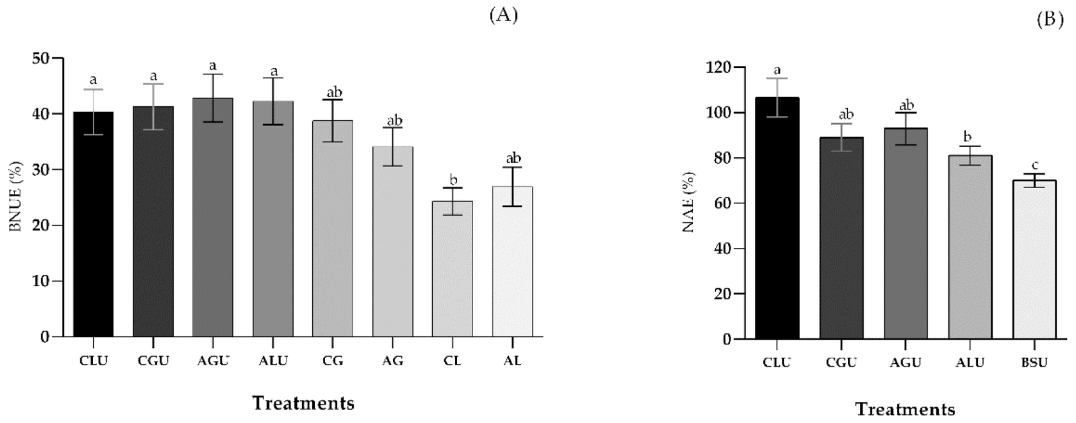

Fig. 5. Biological nitrogen use efficiency (BNUE) (A); Nitrogen agronomic efficiency (NAE) (B) in the experimental treatments (%). Different letters indicate difference at the 5% level by Duncan's test.

when lower values of rainfall index occur, which may be important to meet the challenge of cooling crops under global warming. According to Marques et al., (2017), the effects of residues of different quality on maize grain yield in the tropics vary from year to year due to differences in the potential of residues to maintain soil water availability in drier years.

4.2. Biomass and fertilizer-N interactions

In turn, the processes that lead to greater N uptake have increased relevance than other benefits of ecosystem services for the sustainable intensification of agriculture in the humid tropics. Indeed, the increase of >70% in N uptake in the AGU and CGU treatments compared to the SBU treatment can be attributed to positive interactions between leguminous biomass with fertilizer-N which may enhancement both soil rootability as well as N availability (Sena et al., 2020).

Interactions between leguminous biomass and fertilizer-N has been reported as a key strategy to overcome the principal challenges of the tropical agriculture, increasing the N use efficiency and avoiding the N loss (Vanlauwe et al., 2001). Indeed, the isolated use of readily available fertilizer-N in humid tropic may create high levels of available N that exceed plant demand and can lead to potential N losses due to high temperature and rain intensity. While applied residue slowly releases N, often after the peak of plant N demand has occurred, leading to N deficiencies (Chen et al., 2014). In fact, plant residues when applied in the soil cause soil inorganic nitrogen changes through process of immobilisation–remineralisation. Soils with prevalent mineralisation process usually promote crop nitrogen uptake or greater risk of nitrogen loss (Gentile et al., 2009). The results depend on the synchronism between the soil inorganic nitrogen change and the crop nitrogen uptake. Therefore, combining fertilizer with residue may serve to match the rate of soil N supply with the rate of plant N uptake, according to hypothesis developed by Vanlauwe et al. (2001).

Furthermore, aside from the nutrients released, interactive effects of combining the application of residues in addition to fertilizer-N may improve soil conditions like water holding capacity increased and soil penetration resistance decreased. These processes may result in higher demand by plants for the fertilizer nutrients and consequently enhance fertilizer nutrient use efficiency (Sena et al., 2020). N uptake is highly dependent on root size and architecture, which must be important variables for managing soil for N acquisition across the soil profile (Dechorgnat et al., 2018). In addition, leguminous biomass proved to be as or more capable of providing N than urea, when treatments with gliricidia (AG, CG) and bare soil with urea (BSU) are compared. In conclusion, differences in N uptake between biomass treatments and controls of approximately 140% suggest that the combined use of green manure and inorganic fertilizers may be a better strategy for taking advantage of ecosystem services in humid tropic by enhancing N uptake by crops, as was suggested by Espinal et al. (2016).

The impact of leguminous biomass on maize performance was also remarkable for both dry matter and grain yield in 2018. Greater dry matter production reflects the greater capacity of an agroecosystem for carbon gains from plant growth and sequestration of decomposed plant residues in soils. In particular, practices such as no-till cultivation (Power, 2010) and gypsum application (Moura et al., 2018) can conserve soil carbon and can reduce the degradation of subsurface carbon. In turn, the increased grain yield permits evaluation of economic benefits of ecosystem services, which would lead to win–win situations, by positive effects of ecosystem services on agricultural production (Villarino et al., 2019). The differences in grain yield among the treatments with both biomass and N (CLU > AGU, CGU, ALU) indicate that factors other than those linked to soil fertility, such as antagonistic interactions between species, may also be involved. According to Thevathasan and Gordon (2004), a number of negative or antagonistic interactions, both competitive and allelopathic, may influence crops in agroforestry systems. Thus, the superiority of the CLU treatments, in terms of N-use efficiency and grain yield, may be explained by the soil cover that is provided by the extended durability of clitoria (a native leguminous tree with lower allelopathic effect on maize) and the high contribution of N by leucaena (Aguiar et al., 2019).

Inorganic nitrogen use efficiency (INUE) can provide information about how ecosystem services may facilitate utilization of applied fertilizer in covered soil, increasing N uptake and decreasing loss, with the purpose of agricultural intensification. Use of perennial legumes in agroecosystems modifies internal cycling processes and increases N-use efficiency within agroecosystems (Power, 2010). Surplus additions of inorganic N, which are currently commonplace, can be reduced under these circumstances, leading to reductions in NOx and N_2O emissions. The improvement of the environment for root growth, increasing N uptake in the CLU and AGU treatments, can account for the increase in INUE of 37% compared to the BS treatment. The absorption of N is highly dependent on root development, while root system growth results in greater uptake and lower N leaching and therefore in greater NUE (Garnett et al., 2009). However, the lower INUE in CG treatments suggests that high rate of N release may have decreased INUE of this biomass combination. In turn, inorganic N increased biological nitrogen use efficiency only in treatments with leucaena, due to the positive effect of inorganic N application on release of biological N for easily degradable organic material with low C/N ratio (FOG, 1988). Again, the synergy between organic and inorganic fertilizer seems to be more effective for agricultural intensification in these circumstances. In turn, nitrogen agronomic efficiency can allow clear assessment of feasibility of use of fertilizer in an agricultural intensification context. Therefore, the result of the combination of clitoria and leucaena (52% > than BSU) presents an opportunity to convince farmers to replace conventional systems with sustainable intensification systems using leguminous trees with inorganic fertilizer.

5. Conclusions

The link between ecosystem services provide by leguminous trees and social economic benefits has been established in this work. Our results confirm that the utilization of an ecosystem services style approach can improve soil quality indicators to help meet the challenges of sustainability and feasibility in agrosystems of the Amazonian periphery. Countering the forces of organic matter decomposition and base cation leaching in the humid tropics, perennial legumes are able to improve the root zone environment, increasing soil organic matter and maintaining the sum of base cations. In addition, and even for this reason, increased uptake of inorganic and organic N by crops resulting from biomass application may have several positive environmental and economic effects, such as: i) continuous intensified production in the same land, which prevents the deforestation of new areas under a shifting cultivation system; ii) avoidance of surplus addition of inorganic N, leading to reductions in NOx and N_2O emissions; iii) increased economic return from nitrogen applied by greater nitrogen use efficiency; iv) and delayed calcium reapplication due to increased recycling of base cations, which may make agriculture more feasible. These findings can contribute to the development of land-use policy in the Amazonian periphery, aiming for the intensification of agriculture in cropped areas to avoid deforestation from shifting cultivation systems.

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CRediT authorship contribution statement

Emanoel G. de Moura: Conceptualization, Data curation, Writing - original draft. **Rafael M. de Sousa:** Investigation, Methodology. **Lorena S. Campos:** Formal analysis, Software. **Anágila J. Cardoso-Silva:** Project administration, Formal analysis. **Sacha J. Mooney:** Supervision, Writing - review & editing. **Alana das C.F. Aguiar:** Funding acquisition, Resources, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aguiar, A.C., Souza, E.A., Cardoso-Silva, A.J., Moura, E.G., 2019. How leguminous biomass can increase yield and quality of maize grain in tropical agrosystems. Legume Res. https://doi.org/10.18805/LR-380.

Aguiar, A.D.C.F., Bicudo, S.J., Sobrinho, J.R.S.C., Martins, A.L.S., Coelho, K.P., Moura, E. G., 2010. Nutrient recycling and physical indicators of an alley cropping system in a sandy loam soil in the pre-Amazon region of Brazil. Nutr. Cycl. Agroecosyst. 86 (2), 189–198. https://doi.org/10.1007/s10705-009-9283-6.

Aguiar, A.D.C.F., Cândido, C.S., Carvalho, C.S., Monroe, P.H.M., Moura, E.G., 2013. Organic matter fraction and pools of phosphorus as indicators of the impact of land use in the Amazonian periphery. Ecol. Ind. 30, 158–164. https://doi.org/10.1016/j.ecolind.2013.02.010.

Anríquez, G., Stamoulis, K., 2007. Rural development and poverty reduction: is agriculture still the key? Development Economics Division ESA Working Paper 04(1) 5–46.

Berenguer, E., Gardner, T.A., Ferreira, J., Aragão, L.E.O.C., Mac Nally, R., Thomson, J.R., Vieira, I.C.G., Barlow, J., Nardoto, G.B., 2018. Seeing the woods through the saplings: using wood density to assess the recovery of human-modified Amazonian forests. J. Ecol. 106 (6), 2190–2203. https://doi.org/10.1111/jec.2018.106.issue-610.1111/1365-2745.12991.

Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56 (3), 777–783.

Baoqing Chen, Enke Liu, Qizhuo Tian, Changrong Yan, Yanqing Zhang. Soil nitrogen dynamics and crop residues. A review. Agronomy for Sustainable Development, Springer Verlag/EDP Sciences/INRA, 2014, 34 (2), pp. 429–442. 10.1007/s13593-014-0207-8. hal-01234828.

Coelho, K.P., Ribeiro, P.R.D.A., Moura, E.G.D., Aguiar, A.D.C.F., Rodrigues, T.L., Moreira, F.M.D.S., 2018. Symbiosis of rhizobia with Gliricidia sepium and Clitoria fairchildiana in an Oxisol in the pre-Amazon region of Maranhão State. Acta Scientiarum. Agronomy 40. https://doi.org/10.4025/actasciagron.v40i1.35248.

Daniells, I.G., 2012. Hardsetting soils: a review. Soil Res. 50 (5), 349. https://doi.org/10.1071/SR11102.

Dechorgnat, J., Francis, K.L., Dhugga, K.S., Rafalski, J.A., Tyerman, S.D., Kaiser, B.N., 2018. Root Ideotype influences nitrogen transport and assimilation in maize. Front. Plant Sci. 9 https://doi.org/10.3389/fpls.2018.00531.

Ellerbrock, R.H., Gerke, H.H., 2018. Explaining soil organic matter composition based on associations between OM and polyvalent cations. J. Plant Nutr. Soil Sci. 181 (5), 721–736. https://doi.org/10.1002/jpln.v181.510.1002/jpln.201800093.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75 (4), 529–538.

Freddy, S.C.E., Edson, C.d.S., Takashi, M., Vin iacute cius, I.F., Paulo, C.E.S.O.T., Marconi, B.T., Karuppan, S., 2016. Utilization of nitrogen (15N) from urea and green manures by rice as affected by nitrogen fertilizer rate. Afr. J. Agric. Res. 11 (13), 1171–1180. https://doi.org/10.5897/AJAR10.5897/AJAR2015.10684.

FAO, IFAD, UNICEF, WFP & WHO. (2018). The State of Food Security and Nutrition in the World 2018: Building Climate Resilience for food security and nutrition. https://doi.org/10.18356/c94f150c-en.

Finney, D.M., White, C.M., Kaye, J.P., 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron. J. 108 (1), 39–52. https://doi.org/10.2134/agronj15.0182.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68 (3), 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014.

FOG, K., 1988. The effect of added nitrogen on the rate of decomposition of organic matter. Biol. Rev. 63 (3), 433–462. https://doi.org/10.1111/brv.1988.63.issue-310.1111/j.1469-185X.1988.tb00725.x.

Garnett, T., Conn, V., Kaiser, B.N., 2009. Root based approaches to improving nitrogen use efficiency in plants. Plant, Cell Environ. 32 (9), 1272–1283. https://doi.org/10.1111/j.1365-3040.2009.02011.x.

Gentile, R., Vanlauwe, B., van Kessel, C., Six, J., 2009. Six Managing N availability and losses by combining fertilizer-N with different quality residues in Kenya. Agric. Ecosyst. Environ. 131 (3-4), 308–314.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. Biol. Fertil. Soils 35 (4), 219–230. https://doi.org/10.1007/s00374-002-0466-4.

Hijbeek, R., Pronk, A.A., van Ittersum, M.K., ten Berge, H.F.M., Bijttebier, J., Verhagen, A., Nicholson, F., 2018. What drives farmers to increase soil organic matter? insights from the Netherlands. Soil Use Manag. 34 (1), 85–100. https://doi.org/10.1111/sum.12401.

Huq, N., Pedroso, R., Bruns, A., Ribbe, L., Huq, S., 2020. Changing dynamics of livelihood dependence on ecosystem services at temporal and spatial scales: an assessment in the southern wetland areas of Bangladesh. Ecol. Ind. 110, 1–13. https://doi.org/10.1016/j.ecolind.2019.105855.

Jun, F., Yu, G., Quanjiu, W., Malhi, S.S., Yangyang, L., 2014. Mulching effects on water storage in soil and its depletion by alfalfa in the Loess Plateau of northwestern China. Agric. Water Manag. 138, 10–16. https://doi.org/10.1016/j.agwat.2014.02.018.

Lützow, M.V., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions–a review. Eur. J. Soil Sci. 57 (4), 426–445. https://doi.org/10.1111/j.1365-2389.2006.00809.x.

Malhi, Y., 2012. The productivity, metabolism and carbon cycle of tropical forest vegetation. J. Ecol. 100 (1), 65–75. https://doi.org/10.1111/j.1365-2745.2011.01916.x.

Marques, G.E.C., Aguiar, A.D.C.F., Macedo, V.R.A., Alves, E.D.P., Moura, E.G., 2017. Nitrogen use and protein yield of two maize cultivars in cohesive tropical soil. J. Agric. Sci. 9, 193–201. https://doi.org/10.5539/jas.v9n3p193.

Mendola, M., 2007. Agricultural technology adoption and poverty reduction: a propensity-score matching analysis for rural Bangladesh. Food Policy 32 (3), 372–393. https://doi.org/10.1016/j.foodpol.2006.07.003.

Moore, T.R., Turunen, J., 2004. Carbon accumulation and storage in mineral subsoil beneath peat. Soil Sci. Soc. Am. J. 68 (2), 690–696. https://doi.org/10.2136/sssaj2004.6900.

Moura, E.G., Portela, S.B., Macedo, V.R.A., Sena, V.G.L., Sousa, C.C.M., Aguiar, A.D.C.F., 2018. Gypsum and legume residue as a strategy to improve soil conditions in sustainability of agrosystems of the humid tropics. Sustainability 10 (4), 1006. https://doi.org/10.3390/su10041006.

Moura, E.G., Sena, V.G., Corrêa, M.S., Aguiar, A.C.F., 2013. The importance of an alternative for sustainability of agriculture around the periphery of the amazon rainforest. Recent Patents Food, Nutrit. Agric. 5 (1), 70–78. https://doi.org/10.2174/2212798411305010011.

Muller, A., Ferré, M., Engel, S., Gattinger, A., Holzkämper, A., Huber, R., Müller, M., Six, J., 2017. Can soil-less crop production be a sustainable option for soil conservation and future agriculture? Land Use Policy 69, 102–105. https://doi.org/10.1016/j.landusepol.2017.09.014.

Mulumba, L.N., Lal, R., 2008. Mulching effects on selected soil physical properties. Soil Tillage Res. 98 (1), 106–111. https://doi.org/10.1016/j.still.2007.10.011.

Pinho, P.F., Patenaude, G., Ometto, J.P., Meir, P., Toledo, P.M., Coelho, A., Young, C.E.F., 2014. Ecosystem protection and poverty alleviation in the tropics: perspective from a historical evolution of policy-making in the Brazilian Amazon. Ecosyst. Serv. 8, 97–109. https://doi.org/10.1016/j.ecoser.2014.03.002.

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. B: Biol. Sci. 365 (1554), 2959–2971. https://doi.org/10.1098/rstb.2010.0143.

Prado, R.B., Fidalgo, E.C.C., Monteiro, J.M.G., Schuler, A.E., Vezzani, F.M., Garcia, J.R., Oliveira, A.P.de., Viana, J.H.M., Pedreira, B. da. C.C.G., Mendes, I.de.C., Reatto, A., Parron, L.M., Clemente, E.de.P., Donagemma, G.K., Turetta, A.P.D., Simões, M., 2016. Current overview and potential applications of the soil ecosystem services approach in Brazil. Pesquisa Agropecuária Brasil. 51 (9), 1021–1038. https://doi.org/10.1590/s0100-204x2016000900002.

Sena, V.G.L., de Moura, E.G., Macedo, V.R.A., Aguiar, A.C.F., Price, A.H., Mooney, S.J., Calonego, J.C., 2020. Ecosystem services for intensification of agriculture, with emphasis on increased nitrogen ecological use efficiency. Ecosphere 11 (2). https://doi.org/10.1002/ecs2.v11.210.1002/ecs2.3028.

Temminghoff, E. E., Houba, V. J. (Eds.). (2004). Plant analysis procedures. https://doi.org/10.1007/978-1-4020-2976-9.

Thevathasan, N.V., Gordon, A.M., 2004. Ecology of tree intercropping systems in the North temperate region: experiences from southern Ontario, Canada. Agrofor. Syst. 61-62 (1-3), 257–268. https://doi.org/10.1023/B:AGFO.0000029003.00933.6d.

Tian, G., Brussaard, L., Kang, B.T., 1995. An index for assessing the quality of plant residues and evaluating their effects on soil and crop in the (sub-) humid tropics. Appl. Soil Ecol. 2 (1), 25–32. https://doi.org/10.1016/0929-1393(94)00033-4.

Van Raij, B., Quaggio, J.A., Da Silva, N.M., 1986. Extraction of phosphorus, potassium, calcium, and magnesium from soils by an ion-exchange resin procedure. Commun. Soil Sci. Plant Anal. 17 (5), 547–566. https://doi.org/10.1080/00103628609367733.

Vanlauwe, B., Aihou, K., Aman, S., Iwuafor, E.N.O., Tossah, B.K., Diels, J., Sanginga, N., Lyasse, O., Merckx, R., Deckers, J., 2001. Deckers maize yield as affected by organic inputs and urea in the West African Moist Savanna. Agron. J. 93 (6), 1191–1199.

Veldkamp, E., 1994. Organic carbon turnover in three tropical soils under pasture after deforestation. Soil Sci. Soc. Am. J. 58 (1), 175–180. https://doi.org/10.2136/sssaj1994.03615995005800010025x.

Villarino, S.H., Studdert, G.A., Laterra, P., 2019. How does soil organic carbon mediate trade-offs between ecosystem services and agricultural production? Ecol. Indic. 103, 280–288. https://doi.org/10.1016/j.ecolind.2019.04.027.

Weyland, F., Mastrangelo, M.E., Auer, A.D., Barral, M., Nahuelhual, L., Larrazábal, A., Parera, A.F., Berrouet Cadavid, L.M., López-Gómez, C.P., Villegas, C., 2019. Ecosystem services approach in Latin America: from theoretical promises to real applications. Ecosyst. Serv. 35 (C), 280–293. https://doi.org/10.1016/j.ecoser.2018.11.010.

Whittinghill, K.A., Hobbie, S.E., 2012. Effects of pH and calcium on soil organic matter dynamics in Alaskan tundra. Biogeochemistry 111 (1–3), 569–581. https://doi.org/10.1007/s10533-011-9688-6.